The Future NASA Space Geodesy Network: New Architectures to Support a Stable and Enduring Terrestrial Reference Frame

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Study Goals

- **To identify cost-effective architectures for the NSGN by:**
  1. Taking advantage of existing, underutilized resources and emerging techniques; and…
  2. Leveraging the outcome to inform robust simulations of network performance.
- **To improve the precision of the TRF by:**
  1. Exploiting collocations on satellites of opportunity to generate space ties between the GPS and SLR geodetic systems; and…
  2. Leveraging innovative Kalman filtering strategies to better separate geophysical signal and technique-specific errors in ground ties of the four geodetic systems.

- **Capitalizing on these resources, and on new techniques, how can we reduce the burden on the future NSGN infrastructure?**
- **Emphasis is on the use of space resources that offer the highest prospects for endurance:**
  - Jason-class altimetry missions
  - GRACE gravity missions
  - Dedicated geodetic missions for SLR (e.g., LAGEOS).

Study Assumptions

- **GPS data can support accurate realization of fundamental TRF parameters.**[1]
  - Realizing accurate scale requires careful calibration of transmitter antenna patterns (e.g., with LEO data).
- **Incorporating GPS data from LEOs yields strong additional benefits.**
  - De-couples frame estimates from GPS draconitic errors (esp. along spin axis)
  - Vastly improves observability and coverage relative to ground network.
- **Existing and emerging assets can be better exploited.**
  - Jason and GRACE missions carry geodetic GPS receivers and feature "space ties" (e.g., between SLR, GPS, DORIS).
  - New GNSS systems (Galileo, Beidou and Glonass) are maturing and will provide important new observations for the frame.
  - DORIS also showing improved promise for TRF realization.[2]
- **Improved analysis techniques offer additional promise**
  - Combining inter-technique data at the observation level
  - Using Kalman filtering approaches to promote improved accommodation of small systematic geophysical signals against the backdrop of technique errors and uncertain ties.

1. Haines et al. (2015). Realizing a terrestrial reference frame using the Global Positioning System, *J. Geophys. Res.*, 10.1002/2015JB012225.
2. Couhert et al. (2018). Systematic error mitigation in DORIS-derived geocenter motion, *J. Geophys. Res.*, 10.1029/2018JB015453.

Study Relies on Parallel Tracks

- **Track I: Processing of real data, combined at the observation level, in innovative network solutions.**
- **Track II: Trade Studies/Simulations to assess candidate future network architectures.**

⇨ *Outcomes from Track I (experiences with real data) inform the strategies and assumptions for Track II (simulations).*

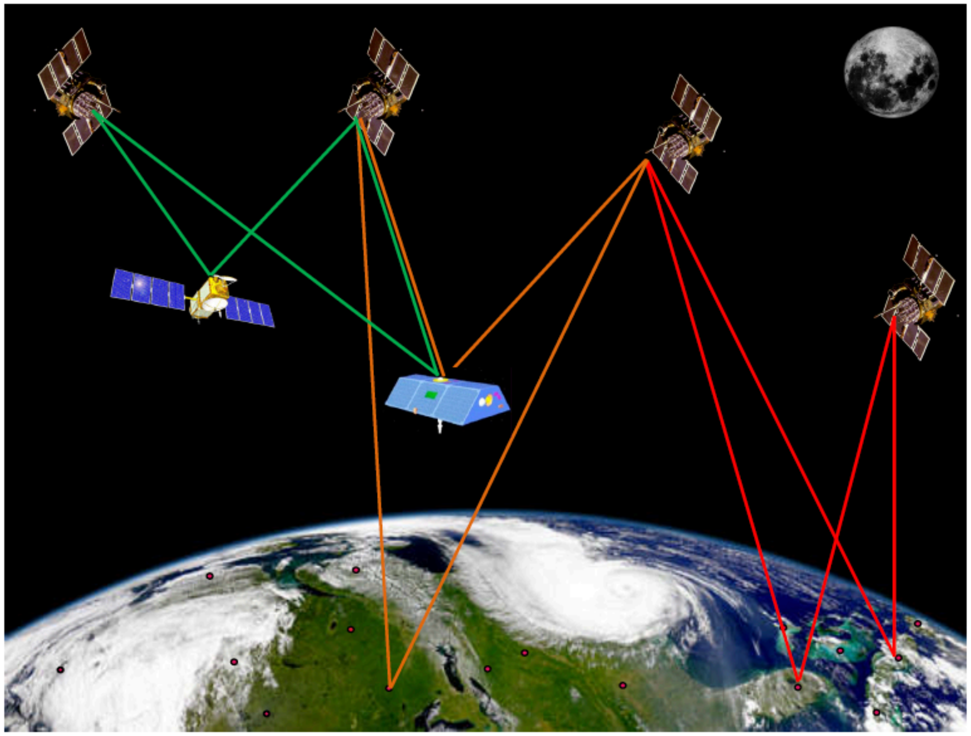
Track I: Processing of Real Data: New Perspectives

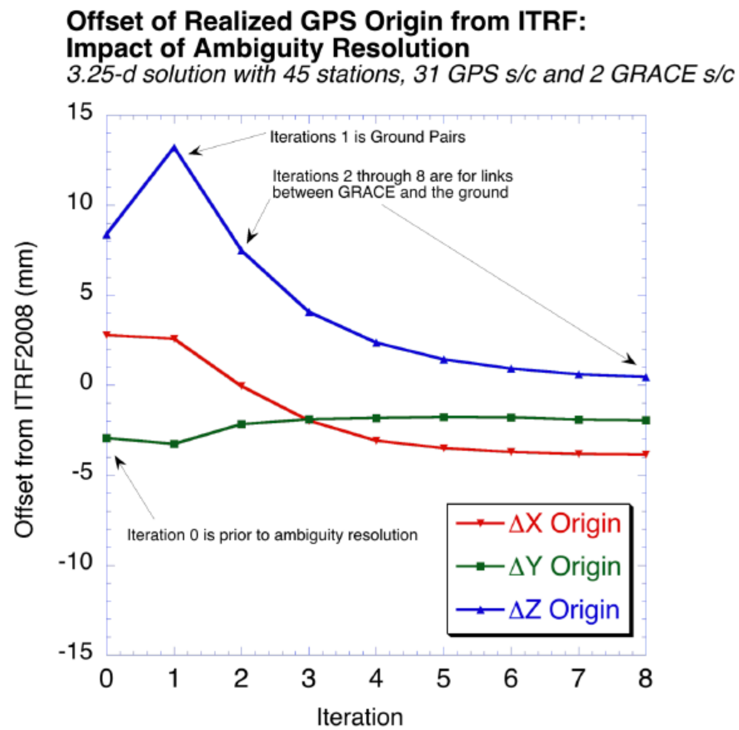
- GPS Only (Ground + LEO)
- GPS and SLR Combined at Observation Level

Highlights of New GPS-Only Solution

- **Space Segment**
  - GPS constellation
  - Three LEOs with precision GPS rcvrs: GRACE A & B and Jason-2
  - All satellite orbits estimated simultaneously
- **Ground Segment**
  - 46 ground sites (exact selection per solution arc based on availability and distribution).
  - Loose (1-km) a-priori constraints on positions ("*Fiducial Free*")
- **New background solar radiation pressure model for GPS satellites**
  - Based on GPS+GRACE+ground network solutions
  - Fiducial-free approach implies independence from prior TRF definition.
- **TRF, EOP and selected geopotential coefficients are simultaneously recovered in 3.25 d solutions**
  - Also addresses weakness of GRACE gravity estimates (e.g., J2).
  - All participating satellites influence gravity, TRF recovery.
- **GPS satellite antenna phase center offsets and variations independent of any TRF definition.**
  - Technique relies on dynamical constraint from POD for TOPEX/Poseidon and GRACE (Haines et al., 2015).
  - Ground and LEO antenna calibrations also independent of frame.
- **GPS phase biases adaptively resolved using new strategy**
  - First, resolve biases involving ground station pairs
  - Second, iteratively resolve biases between ground stations and LEOs

Resolving Ambiguities Using Adaptive Approach



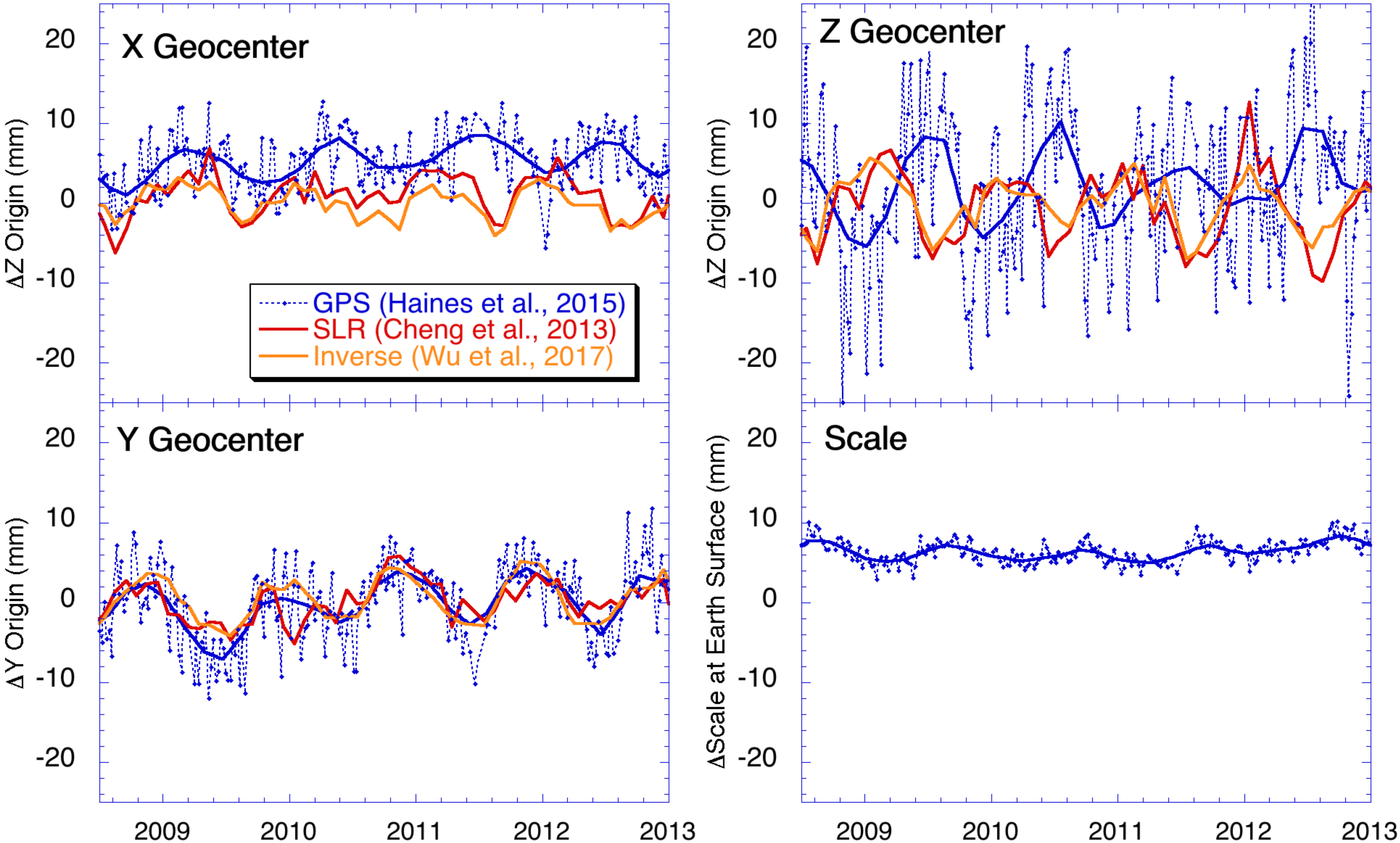


GPS carrier phase biases are resolved iteratively; first constraining double differences involving pairs of ground stations (red links), and then constraining double differences between LEOs and the ground (orange links). The ambiguity resolution strategy for the LEO/ground links is tuned for the shorter common visibilities afforded by the rapidly-changing geometries. Double differences between pairs of LEOs (green links) have also been successfully resolved.

Haines et al., GRACE Science Working Team Meeting (2018)

Prior Result: TRF Realized with GPS Alone (vs. ITRF2014$_{IGS14}$)

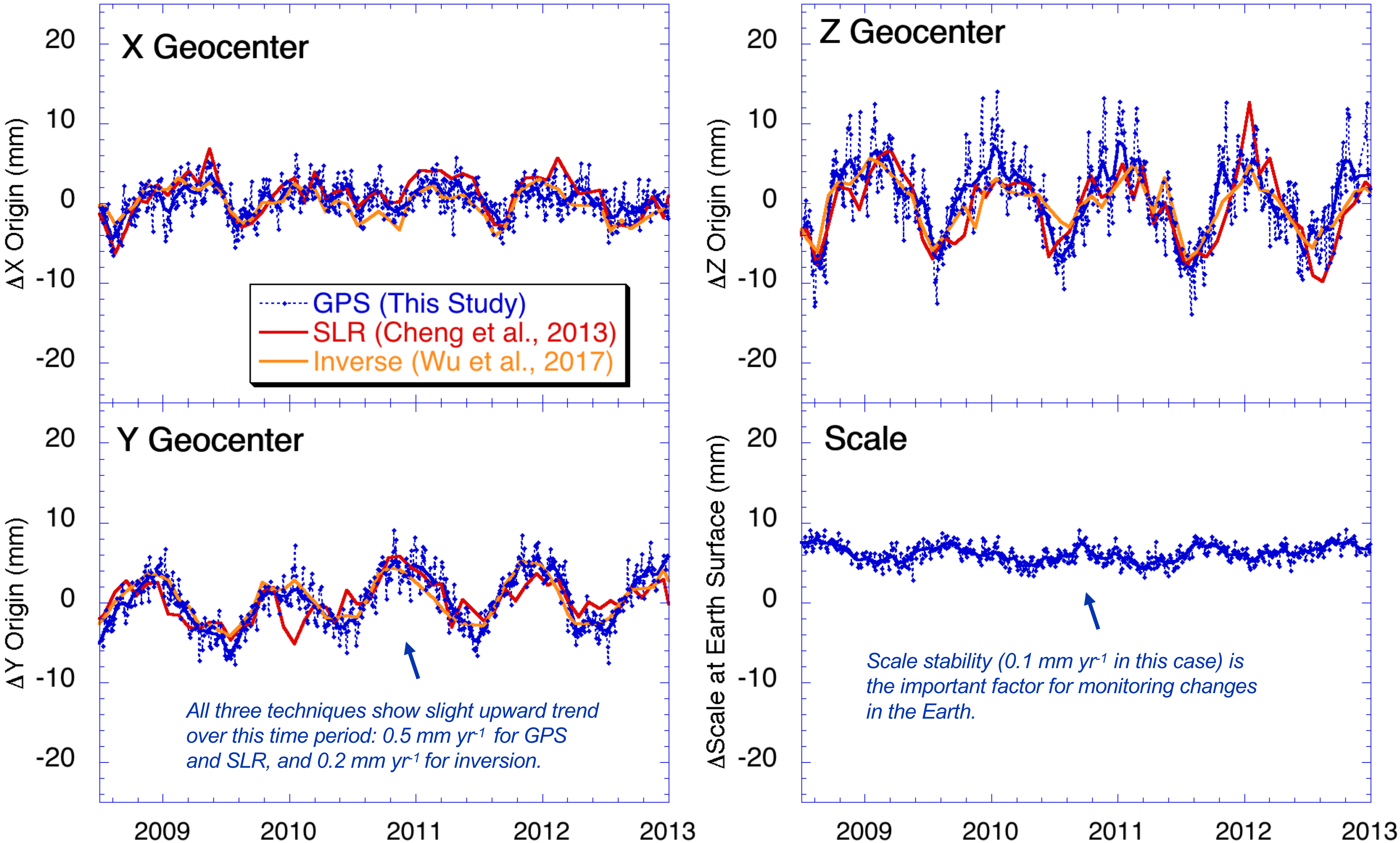
GPS Constellation + Ground Network (Haines et al., 2015)



Haines et al. (2015). Realizing a terrestrial reference frame using the Global Positioning System, J. Geophys. Res., 0.1002/2015JB012225.

New Result: TRF Realized with Grand GPS Network Solution (vs. ITRF2014$_{IGS14}$)

GPS Constellation + Ground Net. + Jason-2 + GRACE A/B, with Adaptive Ambiguity Resolution



Annual Geocenter Motion:
Comparison of Recent Solutions

Solution	X		Y		Z	
	A (mm)	ϕ (d)	A (mm)	ϕ (d)	A (mm)	ϕ (d)
SLR CSR (Cheng et al., 2013)	2.7	40	2.8	323	5.2	30
SLR ILRS (Altamimi et al., 2016)	2.6	46	2.9	320	5.7	28
DORIS Jason-2 (Couhert et al., 2018)	1.6	13	3.2	322	6.4	18
Global Inversion GPS def. + GRACE + OBP (Wu, 2019)	2.0	36	3.3	332	3.7	26
GPS GRACE GRACE POD + accel. (Kuang et al., 2019)	1.1	54	2.8	332	3.6	45
GPS Network Ground + LEO 2008–2012 (this study)	1.5	66	3.6	342	5.5	15
Mean, Std. Dev.	**1.9 ± 0.6**	**43 ± 18**	**3.1 ± 0.3**	**329 ± 8**	**5.0 ± 1.1**	**27 ± 11**

TRF Realizations from GPS Data Alone:
Comparison of Fundamental Frame Parameters to ITRF2014$_{IGS14}$

	Years (Duration)	Offset (mm) on Jan. 1, 2010 X	Y	Z	S	Drift (mm yr^{-1}) X	Y	Z	S
GPS Ground (Haines et al., 2015)	1997–2013 (16.8 yr.)	–4.4	–1.3	–2.0	+4.7	–0.3	**+0.1**	–0.4	+0.2
GPS Gnd. + GRACE (Haines et al., 2015)	2003–2013 (10.8 yr.)	–2.6	**–0.3**	**–0.1**	+4.9	–0.2	**+0.1**	**–0.1**	+0.2
GPS Grand Network (This Study)	2008–2012 (4.5 yr.)	**–0.9**	**+1.0**	**+1.0**	+4.8	**+0.1**	–0.5	**+0.1**	**–0.1**

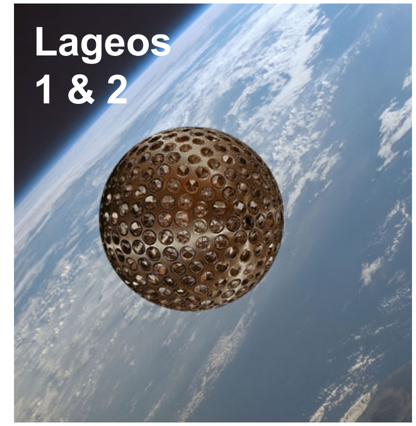
- **ITRF14: origin from SLR; scale from SLR + VLBI.**
- **GPS TRFs: origin and scale from GPS alone.**

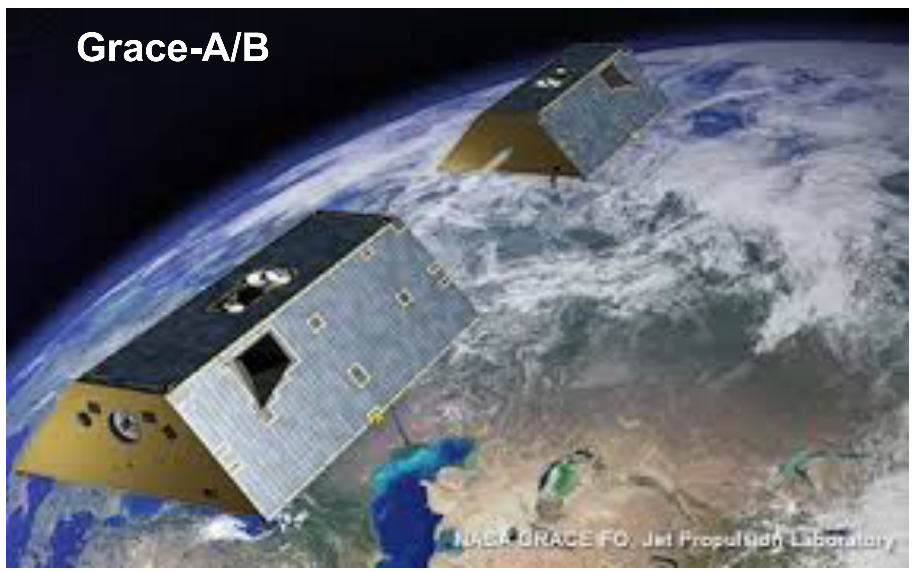
Adding SLR at the Observation Level:
Key Features of Prototype "Grand" Solution

- **Super network of ~40 s/c and ~60 ground stations**
  - GPS constellation
  - Dedicated geodetic satellites for SLR ranging
  - Jason and GRACE missions (GPS/SLR collocation)
  - GPS and SLR ground sites (with no a-priori constraints on positions).
- **GPS and SLR combined at the observation level**
  - GRACE K-band range (KBR) also included
  - GRACE acclelerometer data optionally included
- **TRF, EOP and geopotential are simultaneously recovered**
  - Also addresses weakness of GRACE gravity estimates (e.g., J2).
  - All participating satellites influence gravity, TRF recovery.
    - "Estimation threshold" for maximum spherical harmonic degree customizable by satellite.
  - Dedicated SLR targets and GPS in LEO important for low-wavelength gravity.
  - KBR important for short-wavelength gravity

Satellites (39 Total) Used in Prototype Solution

Jason-2 and GRACE Tandem Yield Crucial GPS data from LEO Perspective, and Provide “Space Tie” between GPS and SLR* (cf. GRASP mission concept).



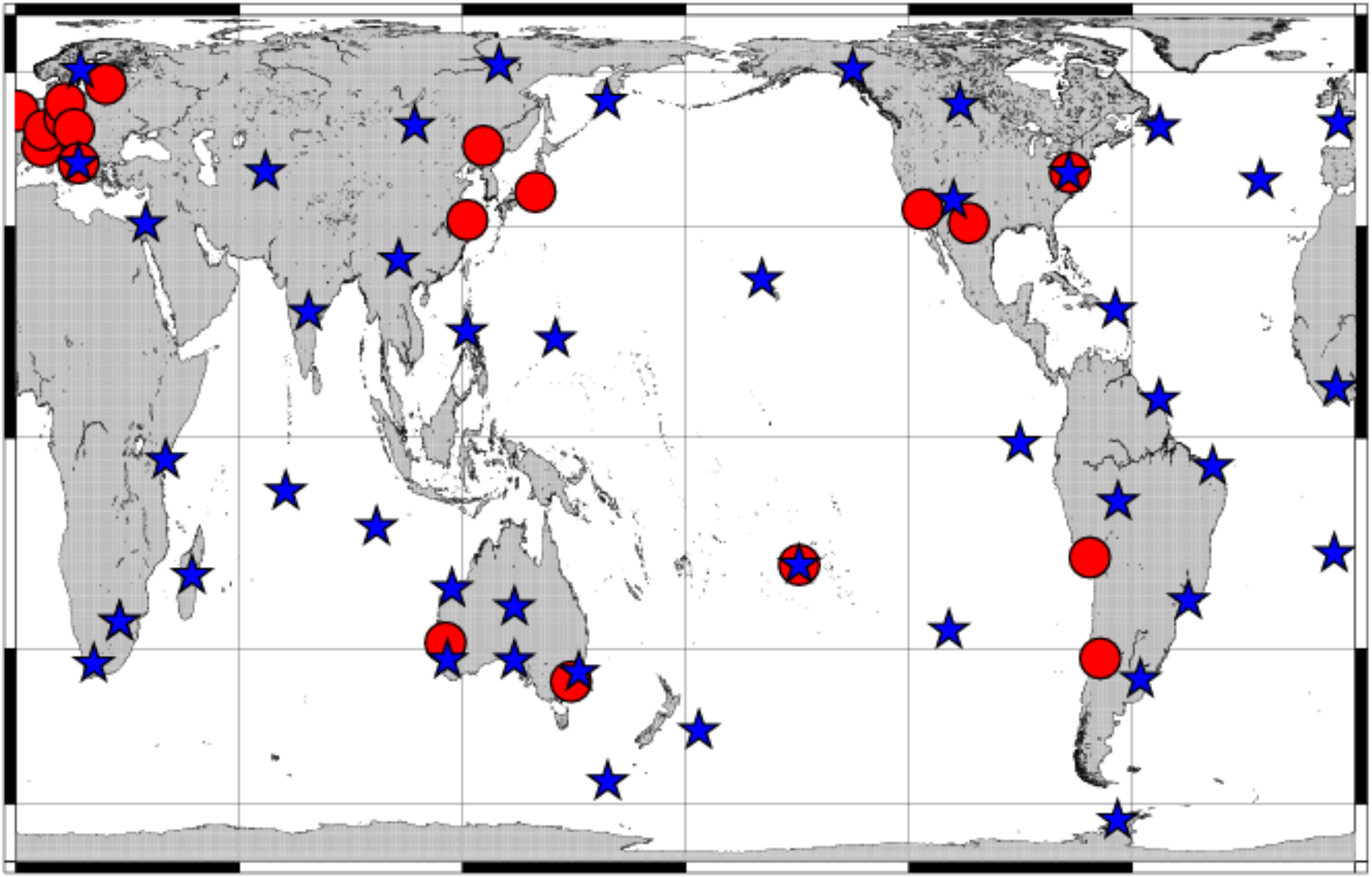


Stations (62 Total) Used in Prototype Solution

43 GPS sites + 17 SLR sites + 2 GPS/SLR collocations (Matera and Tahiti)

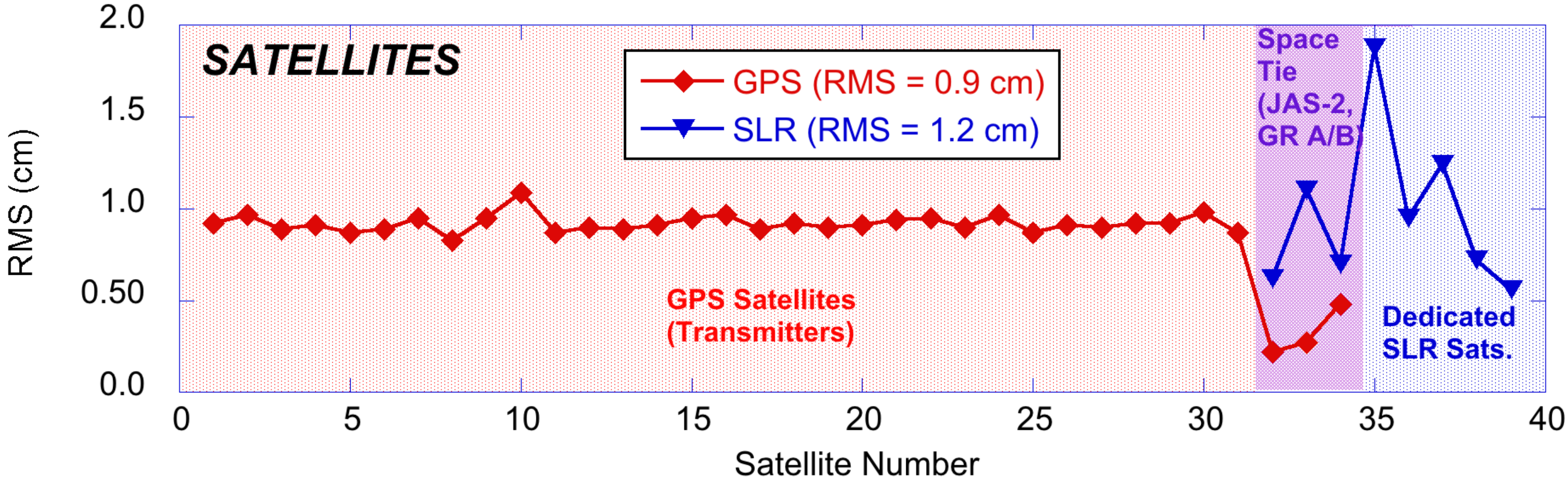
GPS

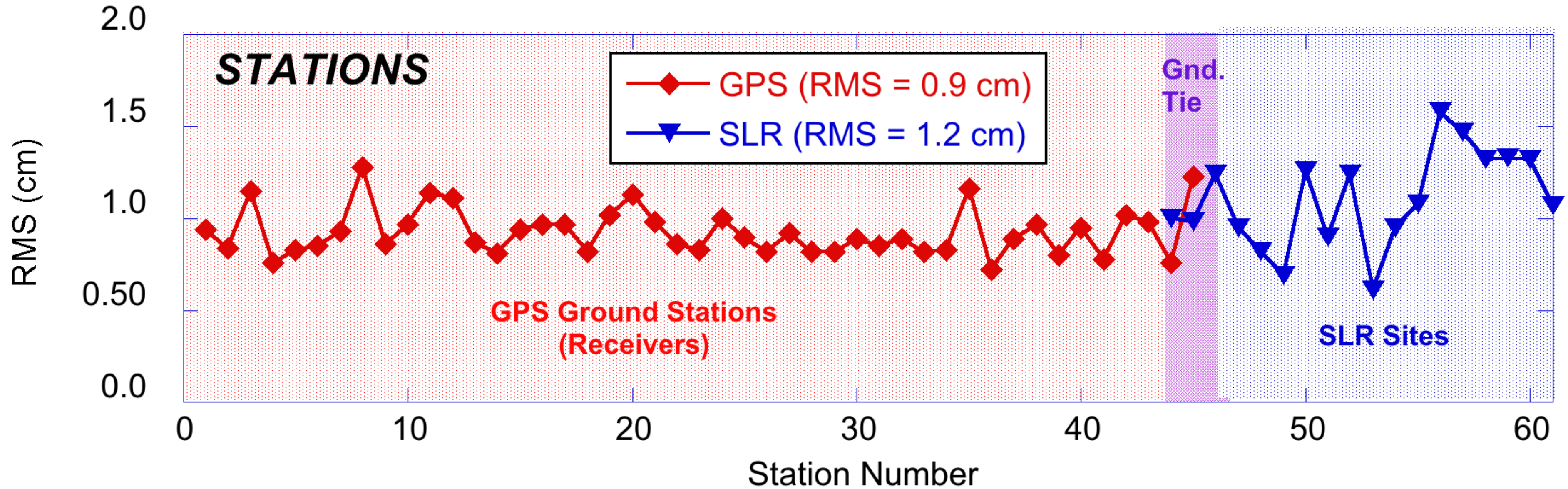
SLR



Tracking Data Residuals for GPS Phase and SLR Range

39 Satellites with 3 Space Ties (Jason-2, GRACE-A and GRACE-B)
62 Ground Stations with 2 Potential Ground Ties* (Matera and Tahiti)

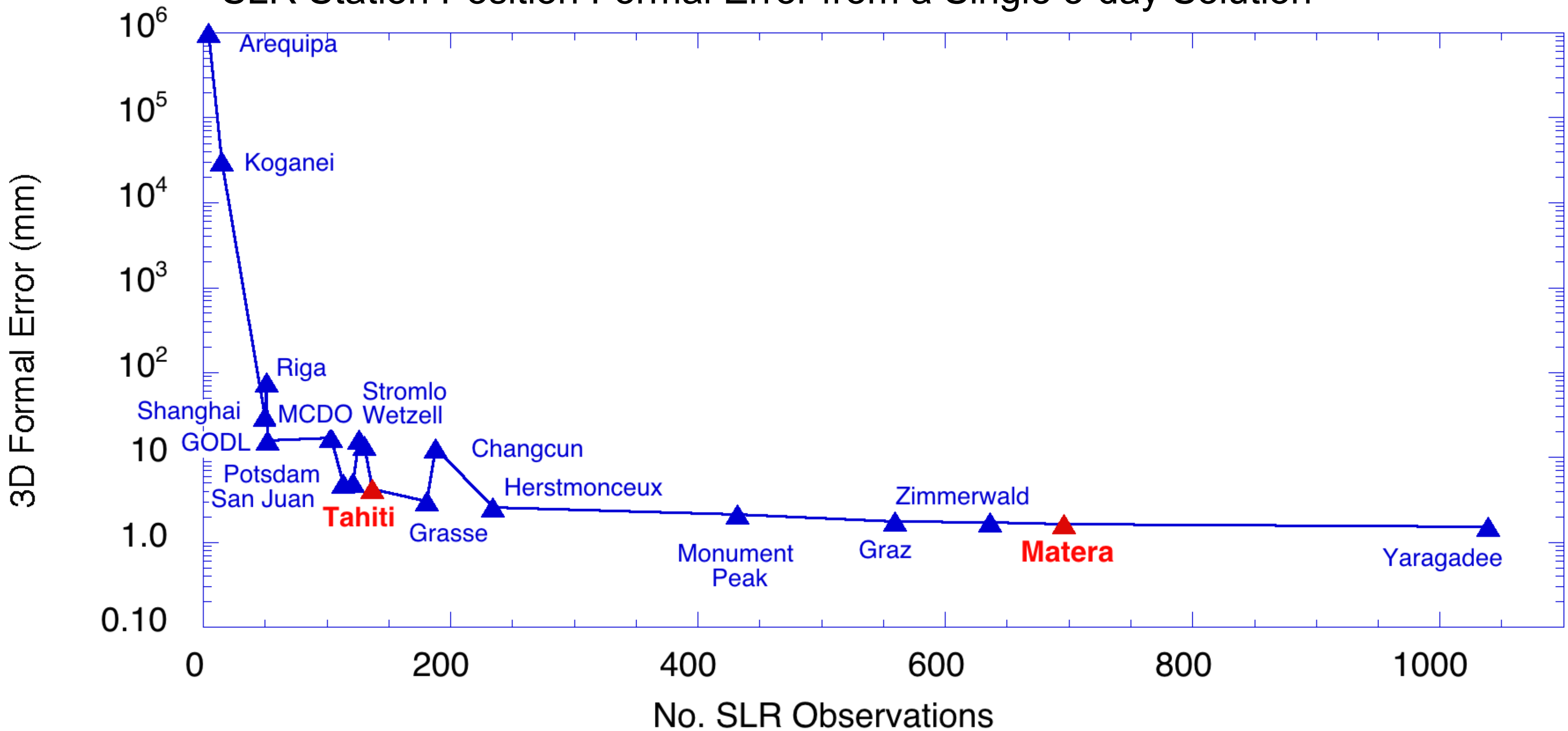




*** Ground ties not used. All GPS and SLR Stations estimated freely and independently (1 km a-priori sigma).**

Recovering GPS/SLR Ground Tie from Space Collocations:

SLR Station Position Formal Error from a Single 3-day Solution



- **Formal errors for most productive SLR sites are "in family" with typical GPS stations (1– 2 mm).**
- **Matera and Tahiti enable a preliminary test of the effectiveness of the space ties**
  - GPS and SLR data from these locations are represented in the solution.
  - Surveyed ground tie is NOT used to connect the two techniques.
  - Only direct connection between SLR and GPS is through space ties (mainly on Jason-2, but also GRACE A/B).
  - With only 3-days of data, ground tie at Matera is recovered to better than 1 cm in all 3 components:
    - (–9.7, –7.4, 7.3) mm in local ENV coordinates
  - Ground tie at Tahiti is recovered to better than 1 cm in lateral components (with only 137 SLR observations).
    - (0.1, –7.9, 24.1) mm in local ENV coordinates.

Track II: Simulations and Trade Studies

- GPS Only (Ground + LEO)
- GPS and SLR Combined at Observation Level

Simulation/Trade Studies: General Approach (1/2)

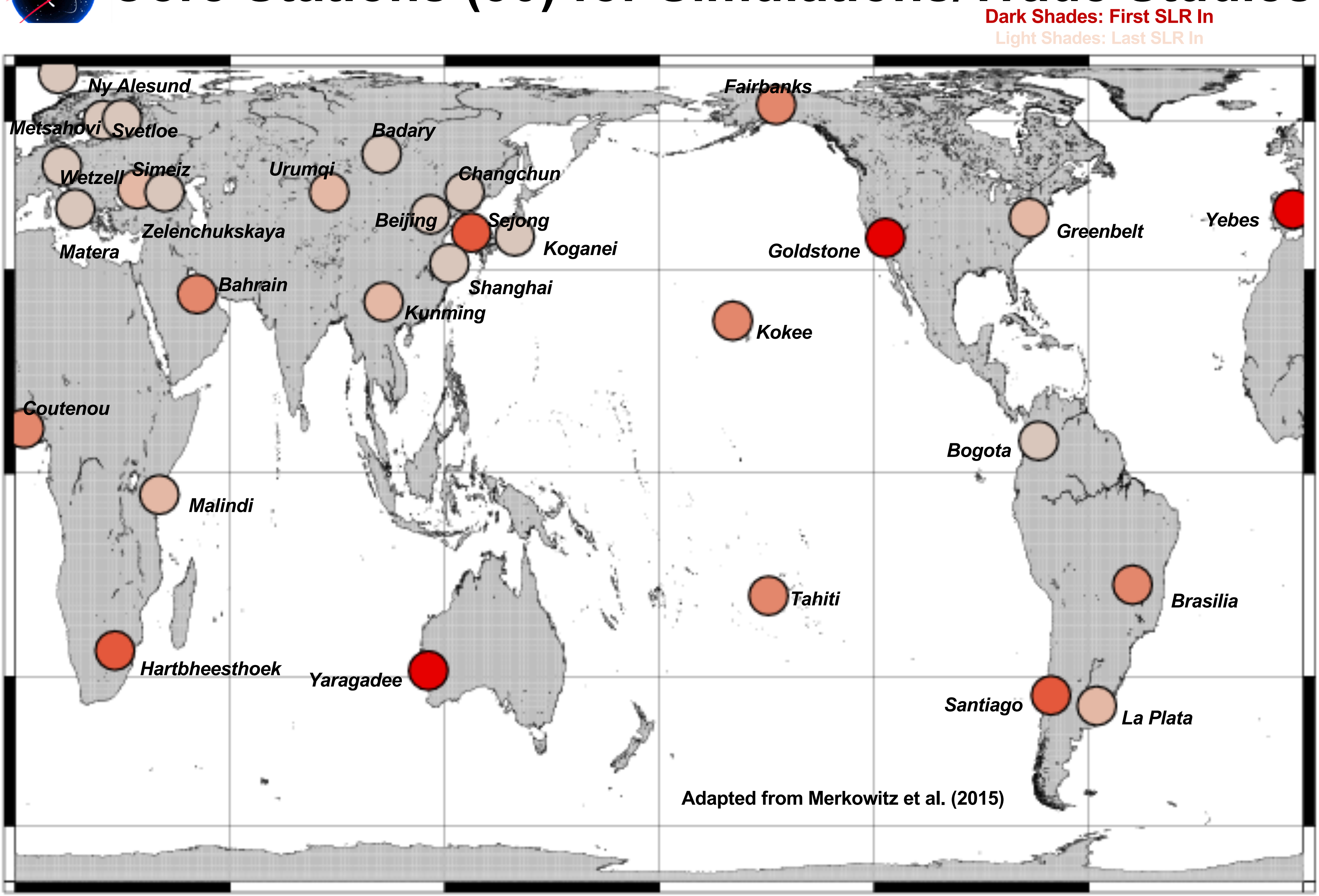
- **Informed by experiences from real data processing**
  - Arc length (3.25 d)
  - Network architecture
  - Tracking data noise/weights
  - Calibration of error model perturbations
- **Ground segment:**
  - 30-station global network of candidate core sites
  - Continuous GPS at all stations
  - SLR collocations varied from 0 (none) to 30 (all)
  - Monthly coordinates developed from geophysical models to reflect real loading/geocenter effects.
- **Space segment:**
  - GPS
  - Jason and GRACE tandem (SLR/GPS space collocations)
  - Dedicated SLR targets: LAGEOS 1 & 2, Stella, Starlette and Ajisai.
- **Simulate GPS & SLR tracking observations with legacy (GIPSY) software**
  - Add white- and/or colored noise to tracking observations
- **Process simulated observations with new (GipsyX) software in the presence of perturbed models.**

Simulation/Trade Studies: General Approach (2/2)

- **Perturb solution with large, systematic GPS errors, especially those that confound traditional ground network approach, as exposed through collinearity issues.[1]**
  - GPS s/c solar radiation pressure: GSPM13 vs GSPM04 (manufacturer's table for IIF).
  - GPS s/c antenna calibrations: IGS standard (from ground data) vs. LEO-based (Haines et al., 2015)
  - GPS gnd. antenna calibrations: IGS std. vs JPL test range (Young et al., 1993) for choke ring.
  - GPS satellite attitude: GIPSY vs GipsyX
  - Troposphere mapping function: Niell vs. VMF1
- **Capitalize on two approaches to overcome GPS collinearity issues:**
  - Add GPS collected in LEO by Jason and GRACE satellites.
  - Incrementally add high-quality SLR stations, based on favorable geometry and weather.
- **Focus on one year's worth of simulations to refine solution space.**
  - Test year consists of 129 overlapping 3.25-d arcs spanning March 2011 to March 2012.
  - Over 50 different scenarios have been run for the test year.
- **Extend evaluation to decade-scale for most promising strategies.**

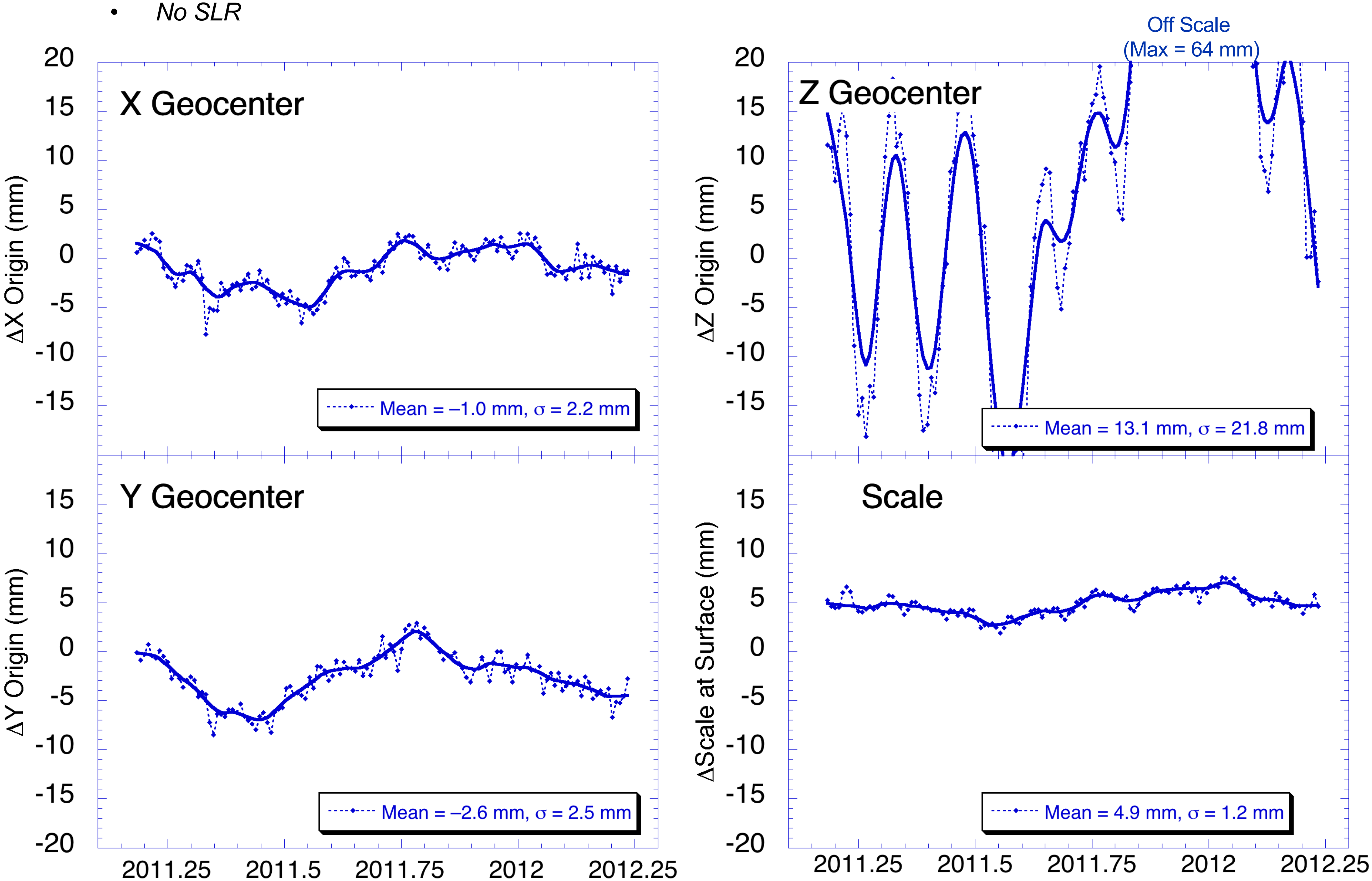
1. Rebischung et al. (2014). A collinearity diagnosis of the GNSS geocenter determination, J. Geodesy, 10.1007/s00190-013-0669-5.

Core Stations (30) for Simulations/Trade Studies



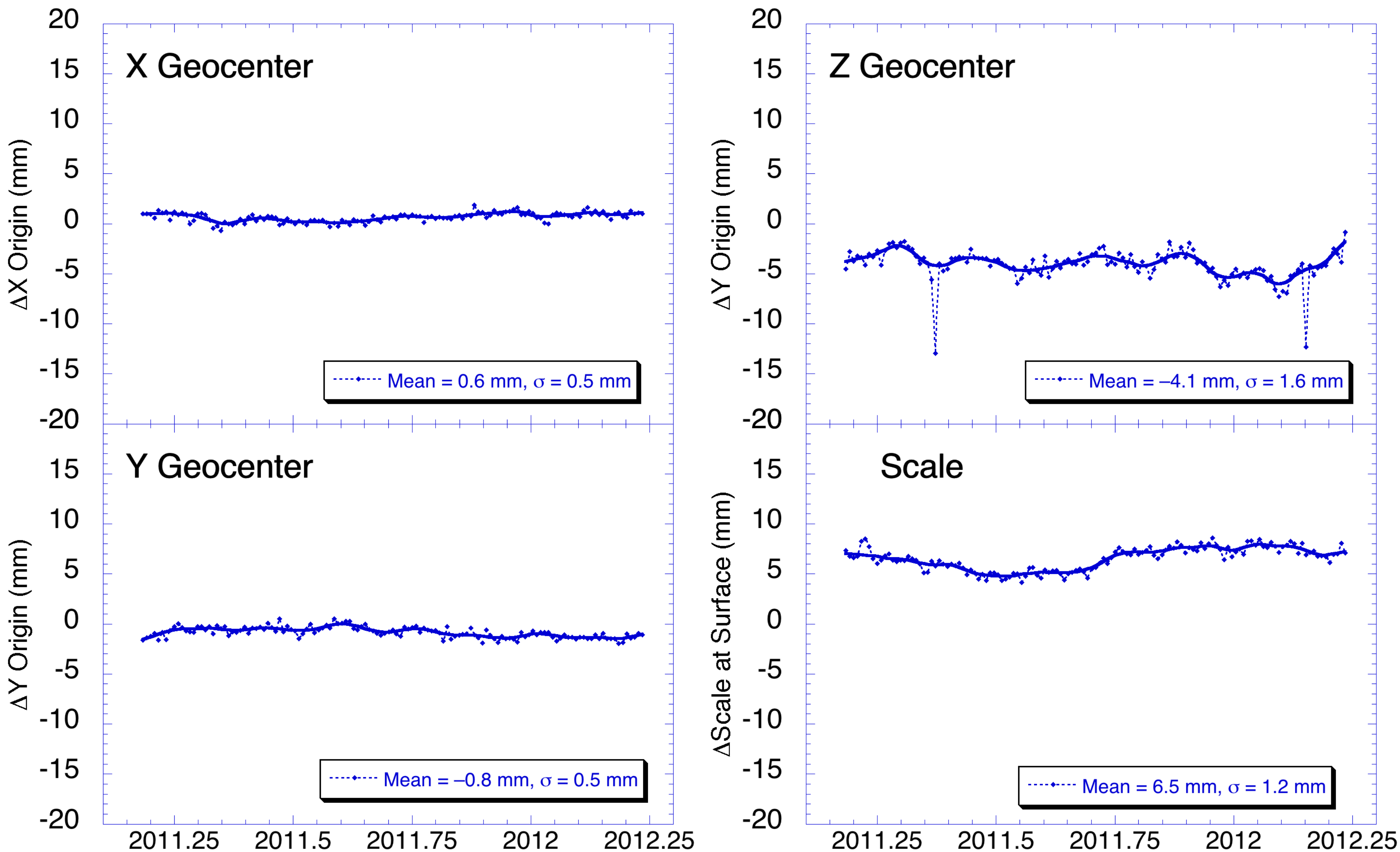
Simulated TRF Error for Deficient (Base) Case: GPS Gnd. Network with Large Errors

- *Continuously operating GPS ground stations at 30 core sites only.*
- *Pessimistic error model for GPS s/c solar rad. pressure, gnd. and s/c antennas, troposphere*
- *No Contribution from GPS in LEO*
- *No SLR*



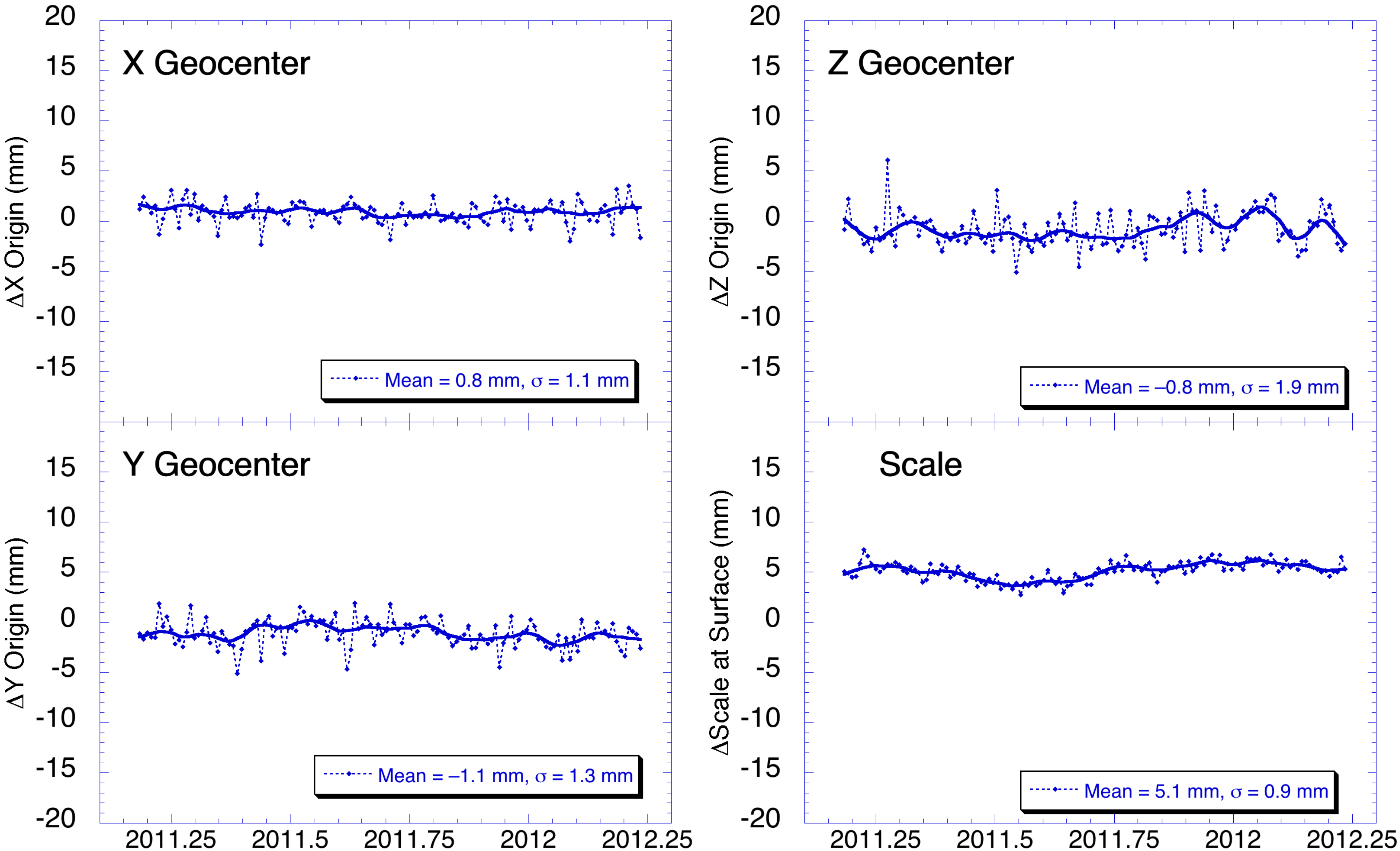
Simulated TRF Error: Supplement Terrestrial GPS Network with LEO GPS

How Well Does GPS LEO Data Overcome Errors in TRF Realization from Terrestrial GPS Network?



Simulated TRF Error: Add SLR at 6 of 30 Core Sites.

How Well Does SLR Overcome Errors in TRF Realization from Terrestrial GPS Network?



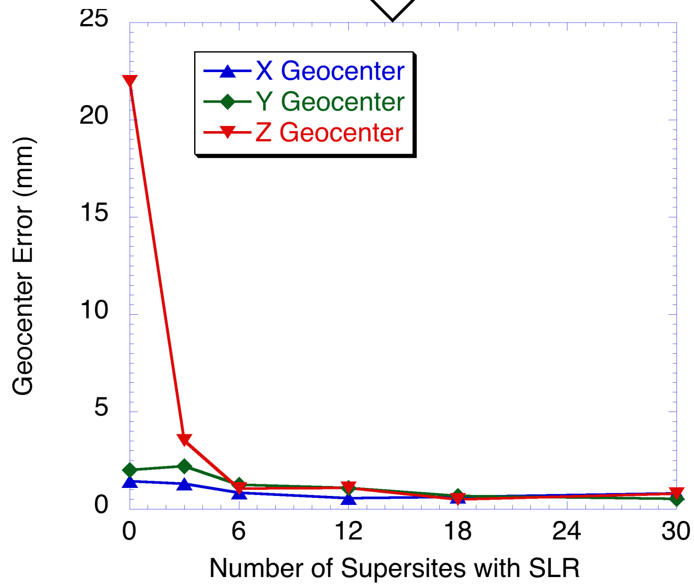
Simulated TRF Error: Incrementally Add SLR to 30 Core Sites

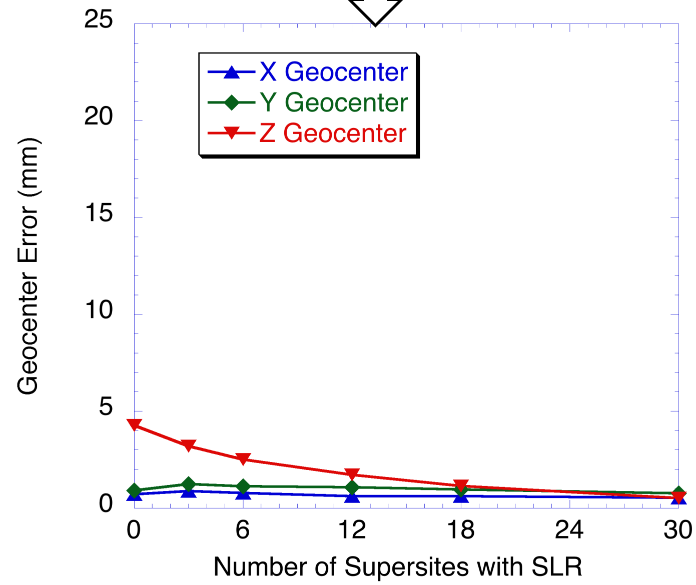
RMS Monthly Geocenter Error *for One Year of Simulations*

GPS Ground + SLR

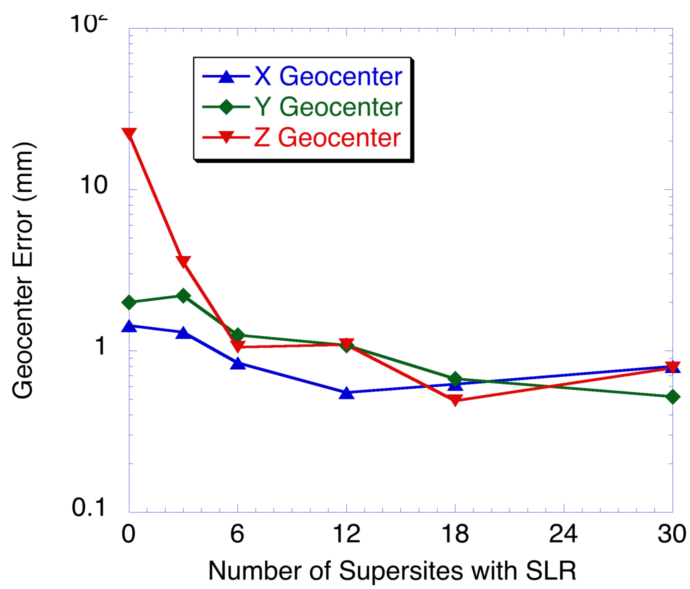
GPS Ground + GPS LEO + SLR

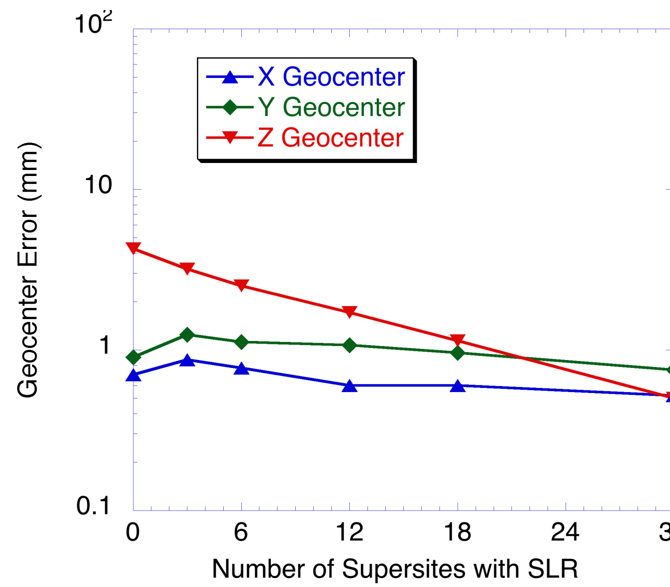
Linear Scale For Ordinate





Log Scale For Ordinate





Conclusions

- **We may be closer to the 0.1 mm yr^{-1} stability goal than we realize**
  - cf., origin and scale rates between GPS frame and ITRF.
- **GPS can be used to accurately realize the TRF, its scale, origin and evolution thereof**
  - Ground data alone sufficient for linear frame (e.g., Haines et al., 2015).
  - LEO GPS data improves accuracy, and enables accurate recovery of geocenter motion (annual amplitude and phase) along all three axes (also Kuang et al., 2019).
  - Outcome is statistically indistinguishable from ITRF (keeping in mind current limitations in our ability to assess TRF accuracy).
- **New GPS strategies lend themselves to rapid update of TRF**
  - Opens possibility of an operational, self-contained and independent GPS solution combining observations from LEOs and ground stations, with cadence of current JPL IGSAC final product (~1–2 week latency).
  - Quasi-instantaneous GPS TRF solutions can be integrated with Kalman filter approach (Wu et al., 2015) to better realize linear and non-linear signals on the fly.
- **Innovative strategies to combine GPS and SLR at the observation level show great promise for informing the design of the future space geodesy network.**
  - Adopting Jason and GRACE as space ties between SLR and GPS shows early promise for verifying and/or supplanting ground survey ties.
  - Even a small number of high-quality SLR stations seem effective at overcoming collinearity issues with GPS ground network approaches.
  - Addition of GPS observations from LEO data (e.g., Jason, GRACE) strongly improve TRF and reveal detailed mm-level geocenter motions obscured in prior GPS solutions.

Next Steps/Future

- **Real data processing**
  - Extend GPS-only time series (with Jason/GRACE) to 2017 (~decade)
  - Include SLR to assess impact on long-term TRF realization (focus on selected highest quality stations).
  - Combine with VLBI/DORIS at coordinate level (already done for 4.5-yr solution).
  - Apply Kalman filter approach to TRF, and assess solution quality.
- **Trade Studies**
  - Select most promising architectures for long-term (decade-scale) evaluation.
  - Align simulation to current buildout status (e.g., McDonald, Ny Alesund…)
  - Refine SLR and LEO error models.
  - Combine SLR and GPS at observation level, and DORIS + VLBI at coordinate level.
  - Use results to inform recommendations (final report/paper).
- **Looking beyond the ROSES proposal**
  - Include other GNSS (e.g., Galileo) at observation level (currently supported).
  - Capitalize on accurate GNSS clocks (e.g., Galileo, GPS III) by better constraining estimates.
  - Include SLR to GNSS (currently supported).
  - Include DORIS at observation level (currently supported).
  - Include VLBI at observation level (coming soon).
  - Unified TRF/EOP and Geopotential field for GRACE (gravity), Jason (sea level) studies and beyond….